International Journal of GEOMATE, May, 2026 Vol.30, Issue 141, pp.56-66
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2026.141.5435
Geotechnique, Construction Materials and Environment

GEOTECHNICAL STABILITY AND ENVIRONMENTAL RISK MITIGATION OF THE MBAH SOERO UNDERGROUND MINE

*Bambang Heriyadi[1], Fariz Aditya[1], Syari Rahma Yanti[1], Fitri Nauli[1], Rahmad Algozi[1]

[1]Mining Engineering Department, Universitas Negeri Padang, Indonesia

*Corresponding Author, Received: 15 Jan. 2026, Revised: 14 Feb. 2026, Accepted: 16 Feb. 2026

ABSTRACT: Underground excavations in historical mining areas require comprehensive geotechnical evaluation to ensure long-term stability and public safety. The Mbah Soero underground coal mine in Sawahlunto City, Indonesia, is a former mining site that has been repurposed as a heritage tourism and educational facility, where tunnel stability and environmental risk mitigation are critical concerns. This study aims to evaluate the geotechnical stability of the underground openings and to develop mitigation strategies based on empirical classification, numerical modeling, and geophysical investigation. Face mapping was conducted at four tunnel faces to characterize rock mass conditions, supported by laboratory testing of physical and mechanical properties, including point load index tests converted to uniaxial compressive strength values. Rock mass quality was assessed using the Rock Mass Rating (RMR) system, with Q-System values estimated through empirical conversion. Numerical stability analysis was performed using finite element modeling in RS2 Rocsience software to determine safety factors and identify critical zones. Electrical resistivity surveys were carried out along three profiles to support subsurface lithological interpretation related to coal-bearing formations. The results indicate that the tunnel system is generally stable, with safety factor values exceeding critical thresholds, although localized zones require monitoring and limited reinforcement. The integrated approach provides a practical framework for stability assessment and risk mitigation in underground heritage mines.

Keywords: Rock Mass Rating; Underground Mine Stability; Numerical Modeling; Electrical Resistivity; Risk Mitigation

1. INTRODUCTION

Underground mines are characterized by complex geological conditions and confined excavation spaces, making them highly susceptible to geotechnical instability [1]. The stability of underground openings is strongly influenced by rock mass quality, discontinuity orientation, groundwater conditions, and excavation geometry [2]. In old or abandoned underground mines, degradation of rock mass conditions over time can significantly increase the risk of roof fall, wall collapse, and block detachment if no proper stability assessment is conducted [3].

The Mbah Soero underground coal mine, located in Sawahlunto City, West Sumatra, Indonesia, is a former colonial-era mining site that has been repurposed as an underground mining museum and heritage tourism destination [4]. Although the mine is no longer operational, sections of the tunnel network are accessible to the public, requiring a higher level of safety assurance compared to inactive mining sites [5][6]. Previous observations and historical records indicate that parts of the tunnel exhibit weathered rock masses, joint-controlled rock blocks, and localized groundwater seepage, which may contribute to potential instability along the tunnel walls and roof [7][8].

Geotechnical evaluation of underground excavations is commonly performed using empirical rock mass classification systems [9]. The Rock Mass Rating (RMR) system and the Q-System are widely applied methods for assessing rock mass quality and estimating tunnel stability [10][11]. These classification systems consider parameters such as intact rock strength, rock quality designation, joint spacing and condition, groundwater influence, and stress-related factors [12][13]. The results can be used to identify stability conditions and provide preliminary recommendations for tunnel support systems, including unsupported conditions or spot bolting in relatively competent rock masses[14].

Field-based geotechnical investigations such as face mapping play an important role in obtaining accurate rock mass parameters for classification analysis [15]. Face mapping enables detailed identification of discontinuity characteristics, lithological variations, and structural controls affecting tunnel stability [16]. In addition, laboratory testing, including point load index testing, can be used to estimate uniaxial compressive strength values, which are essential input parameters for rock mass classification and stability evaluation[17][18].

To enhance the reliability of empirical assessments, numerical modeling is frequently employed to analyze stress redistribution and stability conditions around underground openings [19]. Finite element–based numerical analysis allows the determination of safety factors and identification of potentially unstable zones under existing geological and geometrical conditions[20]. Numerical results can be integrated with empirical classification outcomes to support geotechnical risk mitigation planning, including stability zonation and evacuation route assessment [21][22].

This study presents a geotechnical stability analysis and environmental risk mitigation assessment of the Mbah Soero underground mine. Face mapping was conducted at four tunnel locations to obtain rock mass parameters for RMR and Q-System classification [23][24]. Tunnel geometry measurements were used to develop two-dimensional and three-dimensional representations of the underground openings. Point load index test results were converted to uniaxial compressive strength values to support rock mass characterization [23]. Furthermore, numerical modeling using RS2 Rocscience software was applied to evaluate safety factors and generate stability zonation maps [25][26]. To support subsurface interpretation and lithological continuity, geoelectrical surveys were carried out along three survey lines consisting of one horizontal and two vertical profiles aligned with the coal seam orientation [27]. The results of this study are expected to provide a comprehensive basis for tunnel stability assessment and geotechnical risk mitigation in underground heritage mines.

2. RESEARCH SIGNIFICANCE

This study evaluates geotechnical stability and environmental risk mitigation at the Mbah Soero underground coal mine, a historical site facing increasing safety challenges due to aging excavations. Rock mass conditions are assessed through face mapping at four tunnel locations using the Rock Mass Rating (RMR) and Q-System to support appropriate ground support decisions. Tunnel stability is further analyzed using RS2 numerical modeling to determine factor of safety zonation, supported by electrical resistivity surveys for lithological interpretation. The study provides practical guidance for underground mine safety and evacuation planning in similar geological settings [28][29].

3. MATERIALS AND METHODS

This study applies an integrated approach combining field investigation, laboratory testing, geophysical surveys, and numerical modeling to evaluate geotechnical stability and environmental risk mitigation at the Mbah Soero underground mine. The research methodology consists of tunnel geometry measurement, face mapping, rock mass classification using the Rock Mass Rating (RMR) and Q-system, laboratory testing through Point Load Index (PLI), electrical resistivity surveys, and numerical analysis using RS2 Rocscience software. Each method is selected to systematically characterize rock mass conditions, assess tunnel stability, and support mitigation planning [30].

3.1 Study Area

The study was conducted at the Mbah Soero underground coal mine, located in Sawahlunto City, West Sumatra, Indonesia. The mine is a historical underground excavation developed during the early RS of coal mining in the Ombilin Basin and currently functions as a heritage and educational site. The underground openings mainly consist of horseshoe-shaped and rectangular tunnels with varying dimensions, many of which were excavated without systematic ground support, resulting in exposed rock masses along tunnel walls and roofs [31].

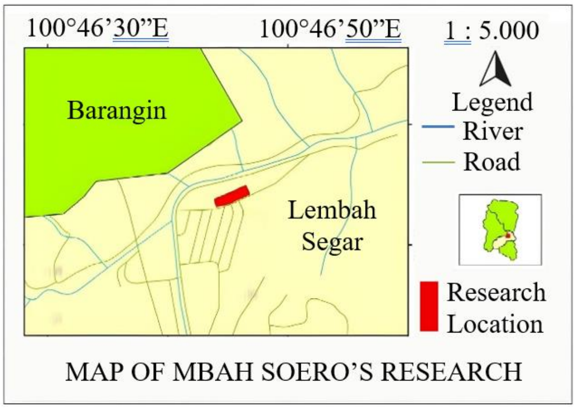

Fig.1 Research location map

Based on the regional geological map of the Solok Sheet, the study area is predominantly underlain by the Sangkarewang Formation. This formation is characterized by sedimentary and volcanic-related lithologies, including calcareous shale, arkosic sandstone, and andesitic breccia.

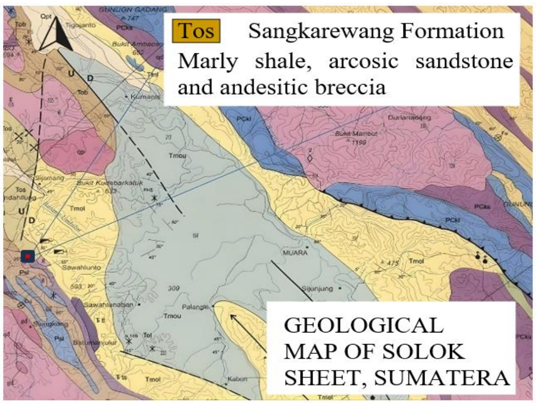

Fig.2 Geological map research area

Structural features such as bedding planes, joints, and local discontinuities are commonly observed along tunnel walls and excavation faces.

Coal seams in the Ombilin Basin generally occur as relatively thin interbeds within sedimentary successions and are therefore not explicitly depicted as separate units on regional-scale geological maps. Locally, underground excavations at the Mbah Soero mine intersect coal-bearing layers that are structurally controlled and spatially associated with specific stratigraphic horizons. Four tunnel faces were selected for detailed face mapping based on lithological variation, structural conditions, and tunnel geometry to represent the spatial variability of rock mass characteristics for subsequent classification and stability assessment.

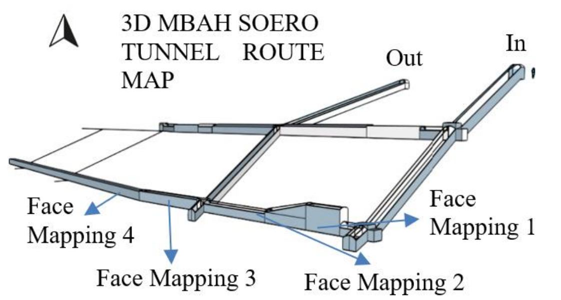

Fig.3 Face mapping area map

3.2 Geotechnical Investigation

3.2.1 Face Mapping

Face mapping was conducted to characterize the geological and geotechnical conditions of the rock mass along the Mbah Soero underground mine. Four tunnel faces were selected as representative observation points based on lithological variation, structural complexity, and exposure quality. The selected faces provide sufficient representation of spatial variability in rock mass conditions within the study area.

Fig.4 Example of face mapping activity at the Mbah Soero underground mine

At each selected face, detailed geological observations were carried out following standard underground rock mass mapping procedures. The recorded parameters include lithology, degree of weathering, discontinuity orientation (dip and dip direction), spacing, persistence, surface roughness, infilling material, aperture, and groundwater conditions. Structural features such as bedding planes and joint sets were identified and documented to evaluate their influence on rock mass behavior and tunnel stability.

Rock Quality Designation (RQD) values were estimated using scanline mapping and volumetric joint count methods, which are widely applied in underground excavations where core data are unavailable[32]. The collected discontinuity data were subsequently used as inputs for rock mass classification using the Rock Mass Rating (RMR) and Q-System methods [13-14].

3.2.2 Physical Properties of Rock

Laboratory tests were conducted to determine the physical properties of rock samples collected from the Mbah Soero underground mine. Representative rock samples were obtained from locations selected during face mapping activities. The measured physical properties included natural density, dry density, saturated density, specific gravity, water content, degree of saturation, porosity, and void ratio.

All laboratory tests were performed in accordance with ASTM standards to ensure the accuracy and consistency of the results. Rock density was specifically determined as a key parameter required for numerical modeling using RS2 Rocscience software. Density values were used as material input data to define the weight of the rock mass in the stress–strain analysis and stability evaluation of the underground openings.

Table 1. Physical properties of rock samples

Parameter	Sample 1	Sample 2	Sample 3
Natural Density (g/cm³)	1.24	1.23	1.23
Dry Density (g/cm³)	1.21	1.22	1.2
Saturated density (g/cm³)	1.25	1.24	1.25
Apparent specific gravity	1.21	1.22	1.2
True specific gravity	1.26	1.24	1.26
Water content (%)	2.41	0.69	2.34
Saturated water content (%)	3.27	1.34	3.58
Degree of saturation (%)	73.88	51.32	65.33
Porosity (%)	3.95	1.64	4.31
Void ratio	0.04	0.02	0.05

The physical property data obtained from laboratory testing served as supporting parameters for rock mass classification and numerical modeling. The test results are presented in Table 1 and were subsequently utilized in the stability analysis and environmental risk mitigation assessment.

3.2.3 Mechanical Properties of Rock (Point Load Index Test)

Mechanical properties of the rock were evaluated using the Point Load Index (PLI) test on representative samples collected from the study area. The test was conducted to estimate the rock strength and provide input parameters for rock mass classification and numerical stability analysis. Due to limited sample size and field constraints, the PLI test was selected as a practical and widely applied method for preliminary strength assessment of rock materials.

The Point Load Index test was performed in accordance with ASTM standards. The measured point load strength index, Is(50), was converted into uniaxial compressive strength (UCS) values using empirical correlation relationships. The estimated UCS values were subsequently used as input parameters in the Rock Mass Rating (RMR) classification and numerical modeling using RS2 Rocsience software.

The mechanical properties obtained from the PLI test are summarized in Table 2, which presents the calculated Is(50) and the corresponding UCS values for each tested rock sample.

Table 2. Mechanical properties of rock samples based on Point Load Index test

Parameter	Sample 1	Sample 2	Sample 3
P (N)	3957	1173	2075
Is (MPa)	0.42	0.20	0.24
F	1.22	1	1.12
Is (50)	0.52	0.2	0.27
UCS (MPa)	12	4.74	6.25

The obtained point load index (PLI) values were converted into uniaxial compressive strength (UCS) using empirical correlations recommended by ASTM standards, and the resulting UCS values were incorporated into the RMR assessment [35].

3.3 Rock Mass Rating and Q-System

Rock mass quality at the Mbah Soero underground mine was quantified using the Rock Mass Rating (RMR) system based on face mapping observations and laboratory test results. RMR values were determined using five primary parameters, including uniaxial compressive strength (UCS), Rock Quality Designation (RQD), discontinuity spacing, discontinuity condition, and groundwater condition, with correction applied for discontinuity orientation. UCS values were estimated from point load index (PLI) tests in accordance with ASTM standards.

The Q-System values were not directly calculated from individual Q-System parameters. Instead, Q values were estimated through empirical conversion from RMR values to provide an approximate indication of rock mass quality for preliminary support evaluation. This conversion approach is commonly applied in cases where complete Q-System parameter data are unavailable or when a rapid assessment is required.

Table 3. Rock mass classification results based on RMR and converted Q-System values

Face	RMR value	Converted Q value
1	56	3.79
2	66	11.52
3	57	4.24
4	50	1.95

3.4 Numerical Modeling for Stability Analysis (RS2)

Numerical modeling was performed using RS2 Rocsience software to analyze the stability of underground openings at the Mbah Soero mine. The analysis employed a two-dimensional finite element method to simulate the mechanical behavior of the surrounding rock mass under in-situ stress conditions. An elasto-plastic constitutive model based on the Mohr–Coulomb failure criterion was adopted to represent rock mass strength characteristics.

When using the Finite Element Method (FEM) for complex geometrical configurations, the coordinate axes are typically aligned with the tunnel's longitudinal and transverse directions. This alignment helps accurately represent stress and deformation and facilitates the precise implementation of boundary conditions [36].

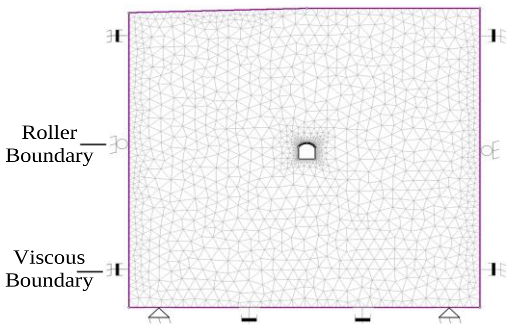

Fig.5 Numerical model and boundary conditions

Boundary conditions were applied by fixing the base of the model in both vertical and horizontal directions and constraining the lateral boundaries horizontally to prevent rigid body displacement [37]. The tunnel geometry was defined based on field observations, while in-situ stress conditions were assumed to be dominated by gravitational loading. Input parameters for the numerical model, including cohesion, internal friction angle, unit weight, Young's modulus, and Poisson's ratio, were determined from laboratory test results and empirical correlations derived from Rock Mass Rating (RMR) values[38].

Table 4. Rock mass parameters used in RS2 numerical modeling

Material	Unit Weight MN/m^3	Young Modulus MPa	Poisson Ratio	Cohesion MPa	Friction Angel ^{o}
Coal	0.0125	2394	0.3	0.3	35

The stability evaluation was conducted using the shear strength reduction (SSR) technique to calculate the factor of safety of the underground openings. The SSR method progressively reduces rock mass shear strength parameters until numerical failure occurs, allowing identification of critical strength reduction factors and potential failure zones [39]. The modeling outputs include factor of safety distributions and strength reduction contours, which were subsequently used to support environmental risk mitigation and evacuation route planning.

3.5 Electrical Resistivity Survey

An electrical resistivity survey was conducted to support lithological interpretation related to the geological conditions of the Mbah Soero underground mine. Due to the limited surface area and heritage protection constraints within the Mbah Soero museum complex, resistivity measurements could not be performed directly above the underground tunnels. Therefore, the survey was carried out at the Ombilin football field area, which provides sufficient open space and is geologically representative of the coal-bearing formations associated with the Mbah Soero mine

The survey location was selected based on the alignment of coal seam strike directions, which are consistent between the Ombilin field area and the Mbah Soero underground mine. This geological similarity allows the resistivity data to be used as supporting information for subsurface lithological interpretation relevant to the underground workings. Three resistivity profiles were acquired, consisting of one horizontal line and two vertical lines, oriented parallel to the dominant coal seam strike to enhance the detection of stratigraphic continuity and structural features.

Data acquisition was performed using Wenner-Schlumberger electrode configurations to capture both lateral and vertical resistivity variations [40]. The measured apparent resistivity data were processed and inverted using RES2DINV (RES2) software to generate two-dimensional subsurface resistivity sections. The inverted models were interpreted by correlating resistivity contrasts with known lithological units and geological observations, providing complementary information to the geotechnical analysis and numerical modeling results

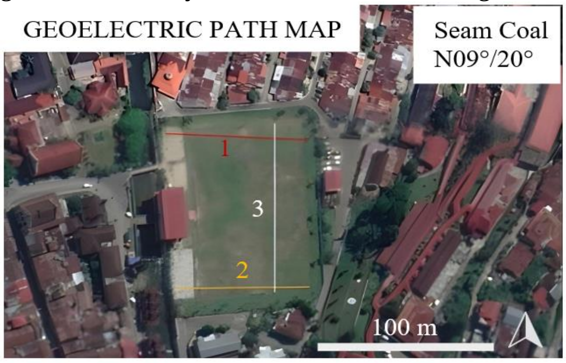

Fig.6 Location and orientation of electrical resistivity survey lines at the Ombilin field area

4. RESULT AND DISCUSSION

4.1 Electrical Resistivity Survey Results

An electrical resistivity survey was conducted to support the interpretation of subsurface lithology and structural conditions associated with the Mbah Soero underground mine. Due to limited open space within the museum area, the survey was carried out at the Ombilin football field, where the orientation of coal seams is consistent with the structural trend of the Mbah Soero mine tunnels. This location was selected to provide representative subsurface information relevant to the underground mining system.

The survey employed the Wenner–Schlumberger configuration, and the acquired data were processed using RES2DINV software to generate two-dimensional resistivity inversion sections. Three survey lines were conducted, consisting of two profiles oriented parallel to the dip direction of the coal seam (Lines 1 and 2) and one profile oriented parallel to the strike direction (Line 3). This survey design allows for the identification of both vertical variation and lateral continuity of subsurface lithological units. The resistivity inversion results from Line 1 reveal a layered subsurface structure with resistivity values ranging from low to moderate. Low-resistivity zones are interpreted as fine-grained sedimentary materials, such as shale or clay-rich layers, which may correspond to coal-bearing strata or water-saturated zones. Moderately higher resistivity zones are associated with more competent lithologies, including arkosic sandstone or volcanic.

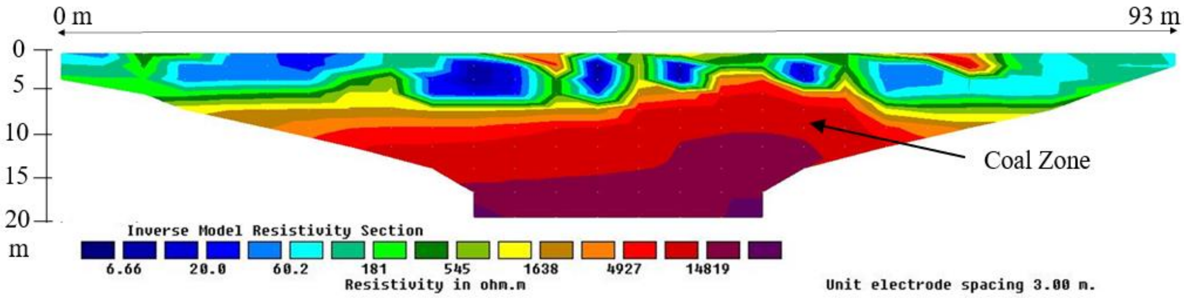

Fig.7 2D resistivity inversion section along Line 1 (dip-oriented profile)

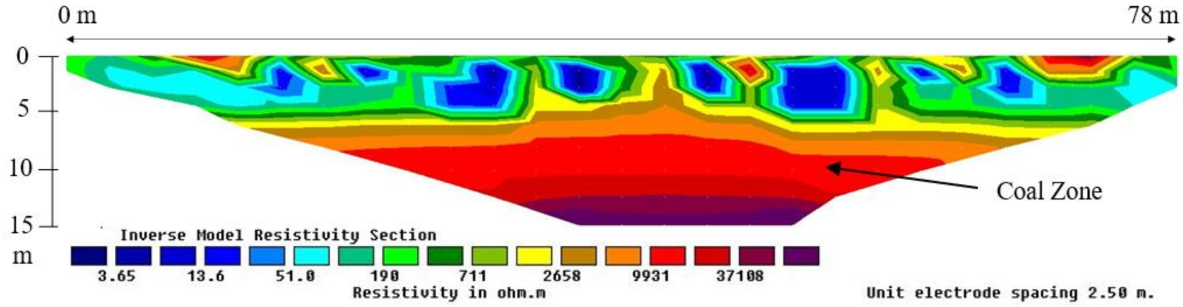

Fig.8 2D resistivity inversion section along Line 2 (dip-oriented profile)

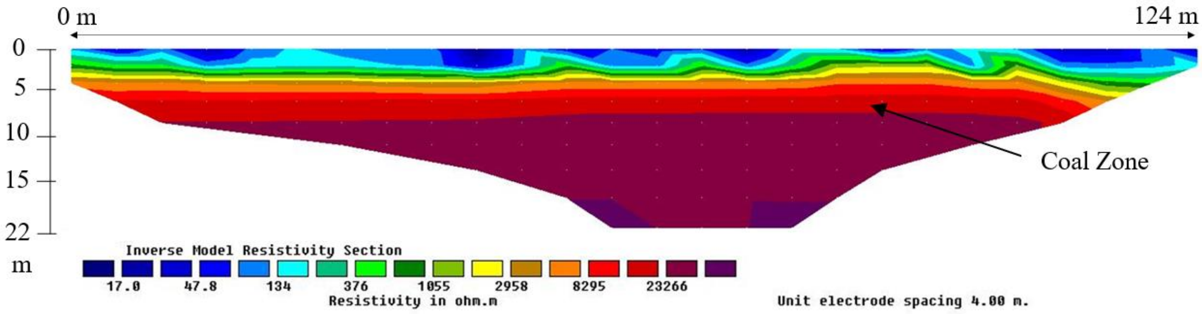

Fig.9 2D resistivity inversion section along Line 3 (strike-oriented profile)

The inversion results from Line 2, which is also oriented along the dip direction, show a similar resistivity distribution pattern, indicating vertical continuity of subsurface layers. Localized low-resistivity anomalies observed at depth suggest the presence of weaker or moisture-rich zones, which may influence the mechanical behavior of the surrounding rock mass.

The resistivity inversion section from Line 3, oriented parallel to the strike direction, highlights the lateral continuity of subsurface units across the survey area. Continuous low-resistivity features along this profile are interpreted as coal-bearing layers or associated fine-grained sedimentary units, while higher resistivity zones represent more massive and competent rock formations. This lateral continuity supports the geological interpretation of coal seam extension in the Ombilin Basin.

4.2 Geotechnical Conditions and Rock Mass Quality

The geotechnical conditions of the Mbah Soero underground mine were evaluated based on face mapping observations, laboratory test results, and rock mass classification using the Rock Mass Rating (RMR) and converted Q-System values.

Table 5**.** Rock Mass Rating (RMR) parameters and ratings for each face

Parameter	Face 1	Face 2	Face 3	Face 4
UCS rating	2	2	2	2
RQD rating	20	20	20	20
Discontinuity spacing rating	10	15	15	15
Discontinuity condition rating	14	19	15	13
Groundwater condition rating	15	15	10	10
Adjustment for joint orientation	-5	-5	-5	-5
Total RMR	56	66	57	50

RMR values range from 50 to 66, indicating fair rock (Class III) to good rock (Class II) conditions according to the classification system proposed by Bieniawski. Converted Q-System values range from 1.95 to 11.52, corresponding to poor to good rock mass quality based on the empirical rock mass classification. These variations reflect differences in lithology, discontinuity spacing, and joint conditions observed along the tunnel faces.

Table 6. Rock mass classification and engineering parameters based on RMR and Q-System

Parameter	Face 1	Face 2	Face 3	Face 4
RMR	56	66	57	50
Rock mass class	III	II	III	III
Rock mass description	Fair rock	Good rock	Fair rock	Fair rock
Stand-up time (5 m span)	1 week	6 months	1 week	1 week
Cohesion, c (kPa)	200–300	300–400	200–300	200–300
Internal friction angle, φ (°)	25–35	35–45	25–35	25–35
Q-System	3.79	11.52	4.24	1.95
Support recommendation	Unsupported or spot bolting	Unsupported or spot bolting	Unsupported or spot bolting	Unsupported or spot bolting

Tunnel sections with higher RMR and Q values are characterized by more competent rock masses with better structural integrity, while lower values are associated with increased joint frequency and less favorable discontinuity conditions. Based on the Q-System classification, most tunnel sections fall within the range where unsupported excavation or spot bolting is considered adequate for stability.

Overall, the geotechnical assessment indicates that the underground openings at the Mbah Soero mine are generally stable under current conditions. However, local reinforcement and routine monitoring are recommended in sections exhibiting lower rock mass quality. The rock mass classification results provide a fundamental basis for numerical stability analysis and mitigation planning, as discussed in the subsequent sections.

4.3 Numerical Modeling of Tunnel Stability Using RS2

Numerical modeling was conducted using RS2 Rocscience software based on the finite element method (FEM) to evaluate the stability of the Mbah Soero underground mine. The model geometry was developed from the actual tunnel dimensions and geological conditions obtained from resistivity measurements and field observations. Rock mass parameters used as input, including unit weight, cohesion, and internal friction angle, were derived from laboratory test results and rock mass classification outcomes presented in Section 3. Density values obtained from physical property testing were incorporated to ensure realistic stress distribution in the numerical model.

In this study, the influence of seismic loading is assessed in RS2 using a pseudostatic implementation, whereby dynamic earthquake effects are represented through equivalent inertial forces applied to the numerical model rather than through full time-history wave propagation analysis.

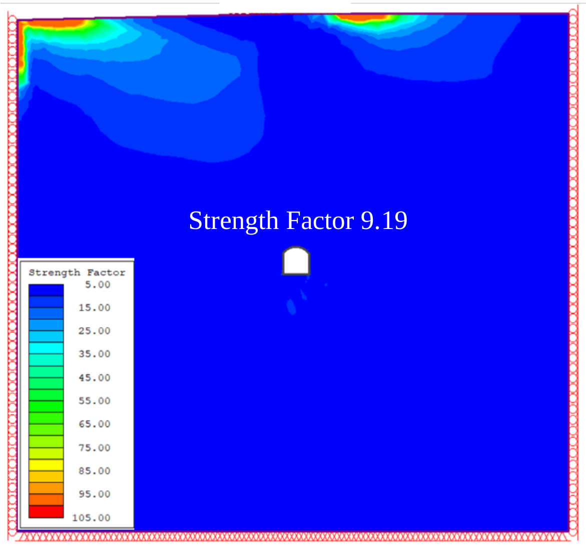

Fig.10 Finite element model of tunnel stability analysis using RS2

The analysis was performed under static loading conditions to represent in-situ stress and self-weight of the surrounding rock mass. The results indicate that the overall tunnel system exhibits stable conditions, with calculated safety factor (SF) values ranging from 7.52 to 15.50 along the tunnel alignment. These values exceed the minimum safety factor commonly adopted for underground openings, indicating a generally safe condition for existing tunnel geometries.

However, localized reductions in safety factor were observed in several segments, particularly between tunnel sections 10 and 13. These zones are characterized by weaker rock mass quality and higher discontinuity density, as identified during face mapping. Although the safety factor in these areas remains above critical limits, the contrast relative to surrounding zones highlights the need for targeted mitigation measures.

4.4 Safety Factor Zonation and Evacuation Route Planning

The safety factor zonation map was developed based on the results of the RS2 numerical analysis to identify spatial variations in tunnel stability along the Mbah Soero underground mine. The zonation classifies the tunnel system into three categories: safe zones, moderately safe zones, and relatively lower safety zones, as shown in Fig. 9. This classification provides a clear visual representation of stability conditions and highlights sections requiring closer attention.

Table 7. Safety factor results from RS2 numerical analysis

Location	FK static	FK Dynamic
1	15.5	13.32
2	10.36	9.19
3	13	11.9
4	12.9	11.09
5	12.26	10.47
6	12.55	10.82
7	12.83	11.16
8	12.66	11
9	12.9	11.01
10	9.2	8.53
11	7.52	6.99
12	9.1	8.5
13	8.6	7.82

Most tunnel segments fall within the safe zone, characterized by high safety factor values and favorable rock mass conditions. These areas are considered suitable for routine access and tourism activities. Moderately safe zones correspond to sections where reduced safety factors were identified, primarily associated with variations in rock mass quality and local structural discontinuities. Although these sections remain stable, periodic monitoring is recommended to detect potential changes over time.

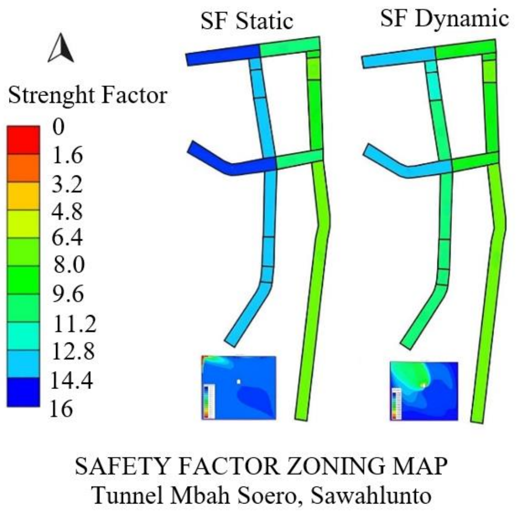

Fig.11 Safety factor zonation map of the Mbah Soero underground mine

Relatively lower safety zones are concentrated in specific tunnel segments, particularly between sections 10 and 13. These zones coincide with lower safety factor values obtained from the numerical model and are interpreted as areas with higher susceptibility to deformation under static loading conditions. As a mitigation measure, localized ground support such as spot bolting and access control is recommended in these areas to reduce potential risks without altering the historical integrity of the tunnel.

Based on the safety factor zonation, an evacuation route map was established to support emergency response planning, as illustrated in Fig. 10.

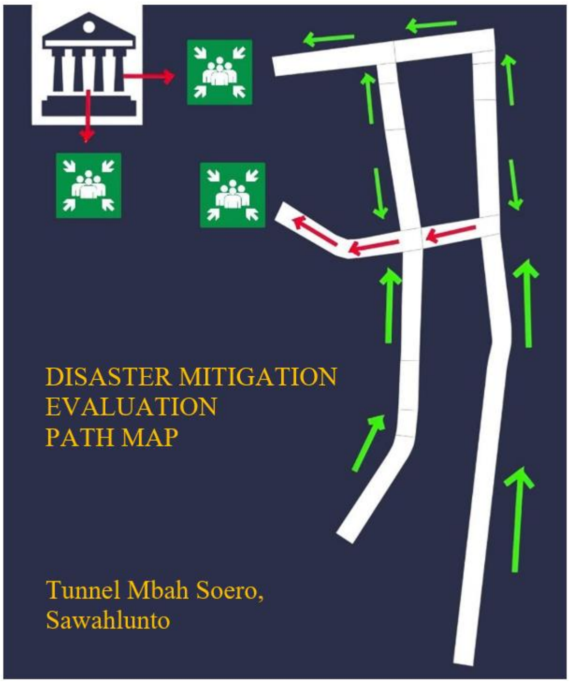

Fig.12 Recommended evacuation routes based on safety factor zonation

The evacuation routes were designed to preferentially pass through tunnel segments classified as safe zones, minimizing exposure to areas with relatively lower stability. Routes were selected based on continuity, accessibility, and proximity to tunnel exits, ensuring that visitors and personnel can evacuate efficiently during emergency situations.

5. CONCLUSION

This study presents an integrated geotechnical stability assessment and environmental risk mitigation analysis of the Mbah Soero underground coal mine, Sawahlunto, Indonesia. Based on face mapping conducted at four tunnel locations, the Rock Mass Rating (RMR) values range from 50 to 66, indicating fair to good rock mass conditions. The corresponding Q-System values vary between 1.95 and 11.52, which places the rock mass within the poor to fair–good quality classes and suggests that most tunnel sections may remain stable with limited or localized support, depending on confinement and structural conditions.

Numerical modeling using RS2 Rocsience software and the finite element method demonstrates that the underground openings are generally stable, with static safety factor values ranging from 7.52 to 15.50. Localized zones with relatively lower safety factors were identified, particularly in tunnel sections 10 to 13, indicating areas that require focused monitoring and minor reinforcement. Safety factor zonation maps derived from numerical modeling were effectively used to define safe, moderately safe, and lower safety zones, forming the basis for evacuation route planning within the underground mine.

Electrical resistivity survey results obtained from three profiles conducted at the Ombilin field area provide supporting subsurface information related to lithological continuity and coal seam orientation. The resistivity inversion sections indicate the presence of low-resistivity zones interpreted as coal-bearing or fine-grained sedimentary layers, confirming geological interpretations of the Ombilin Basin and supporting the geotechnical analysis.

The main novelty of this study lies in the explicit integration of empirical rock mass classification, finite-element stability modelling, and geophysical imaging within a single assessment framework tailored to a historical underground mine environment. This combined approach enables both mechanical stability evaluation and spatial validation of geological controls, offering a more reliable basis for safety planning than any single method alone. The framework is particularly relevant for heritage underground sites where direct investigation may be limited but safety management remains critical.

Future work could extend this approach by incorporating time-dependent effects such as weathering, groundwater fluctuations, or seismic loading, as well as by integrating monitoring data to enable model calibration and long-term stability prediction. Application of the proposed methodology to other historical underground mines or weak rock environments would further test its transferability and support the development of standardized assessment procedures for underground heritage conservation and risk mitigation.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the Directorate of Research and Community Service (DPPM), Directorate General of Research and Development (Ditjen Risbang), Ministry of Higher Education, Science, and Technology (Kemendikti Saintek) for providing financial support for this research (Contract No. 088/C3/DT.05.00/PL/2025). Appreciation is also extended to the Cultural Office of Sawahlunto City and the management of the Mbah Soero Underground Mine Museum for granting permission and access to the study area. The authors thank Universitas Negeri Padang for institutional support, research facilities, and laboratory services that made this study possible. The assistance of field and laboratory personnel during data collection, testing, and analysis is also sincerely acknowledged.

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